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1 Description

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3 Method and device for voltage measurement

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The invention relates to a method for measuring the voltage at a point in a power distribution network by means of a measuring circuit, which has a voltage sensor, which is coupled to a current-carrying conductor of the network, and a further-processing arrangement, which is connected to the

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10 voltage sensor, and outputs a measured voltage value as the

11 output signal at its output, and to an apparatus for

12 carrying out this method.

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In power distribution networks, preferably in the voltage 14 range of 6-20 kV, at present devices are still predominantly 15 used for protection and control purposes which represent 16 directionally independent overcurrent protection. This is 17 sufficient in networks having a central supply and in which 18 the current direction is predetermined. In the case of a 19 20 decentralized supply, however, it is also necessary, for the response of protective devices, for the direction of a 21 current to also be detected, in addition to the level of the 22 current. This can be determined by additional voltage 23 measurements in the network. For this purpose, inductive 24 voltage transformers are generally used today as the voltage 25 sensors. They make it possible to measure the voltage 26 accurately, but represent a considerable cost factor, in 27 particular if they are installed retrospectively in existing 28

29 30 networks.

The German laid-open specification DE 23 25 449 Al describes the use of a capacitive voltage transformer as a voltage sensor for the purpose of measuring the voltage in highvoltage switchgear assemblies, said voltage transformer being formed from a current-carrying conductor of the highvoltage network and an electrode embedded in a post insulator of the conductor. Such capacitive voltage

38 transformers are generally used today, however, merely for

establishing the presence of a voltage having a specific 1 2 minimum level on a line of a power distribution network the 3 displacement current of a high-voltage coupling capacitor, since the measurement result obtained is sometimes relatively inaccurate, with the result that it can only be 5 used to establish the presence of the voltage but not to 6 determine its precise value. 7 8 The object of the present invention is to specify a method 9 and an apparatus of the abovementioned type, by means of 10 which accurate voltage measurement can be carried out 11 irrespective of the type of voltage sensor. 12 13 In terms of the method, this object is achieved according to 14 the invention by the fact that, in a method of the mentioned 15 type, the output signal from the measuring circuit is 16 corrected so as to achieve a correct measured value by means 17 of a correction element having a transfer function which is 18 inverse to the transfer function of the measuring circuit. 19 As a result of the fact that the output signal from the 20 measuring circuit is corrected so as to achieve a correct 21 measured value by means of a correction element having a 22 transfer function which is inverse to the transfer function 23 of the measuring circuit, it is possible, using 24 comparatively simple means, for sufficiently accurate 25 voltage measurement to be carried out irrespective of the 26 type of voltage sensor. 27 28 The method according to the invention can advantageously 29 provide for a capacitor device to be used as the voltage 30 sensor of the measuring circuit. The use of a capacitor 31 device - i.e. a capacitive voltage transformer - as the 32 voltage sensor represents a comparatively cost-effective 33 34 possibility for voltage measurement.

- In this context, it is also regarded as advantageous if a 36
- coupling capacitor, formed from the current-carrying 37
- conductor of the network and an electrode which is 38

DC-isolated from said current-carrying conductor, is used as 1 2 the capacitor device. Such capacitor devices have a comparatively simple design; in addition, capacitor devices 3 of this type are already often provided, for example, in 4 high-voltage bushings of switchgear cells. 5 6 As an alternative, however, it is also advantageously 7 possible to provide for an inductive voltage transformer, 8 which is connected on the primary side to the 9 current-carrying conductor, to be used as the voltage 10 sensor. This is regarded as being particularly advantageous 11 because such an inductive voltage transformer generally 12 makes very accurate voltage measurement possible. Since, 13 however, the measuring circuit can also have a transfer 14 function which slightly falsifies the measured voltage value 15 16 when an inductive voltage transformer is used, even more accurate measured voltage values can be achieved in this 17 case too when using the correction by means of the 18 correction element in accordance with the method according 19 to the invention. 20 21 In this case, however, it is also regarded as advantageous 22 if a correction element is used which can optionally be 23 bypassed via a switch. In this manner, the correction 24 element can easily be bypassed if the measured voltage 25 values achieved using the inductive voltage transformer are 26 sufficiently accurate; in such a case no correction of the 27 measured voltage values therefore takes place. 28 29 Depending on whether the output signal from the measuring 30 circuit is analog or digital, an analog or digital filter 31 32 having a transfer function which is inverse to the transfer 33 function of the measuring circuit can be used as the 34 correction element. The analog filter expediently simulates

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When using a digital filter, a temporally discrete transfer function is suitable as the inverse transfer function. This

a transfer function having a PID characteristic.

can be generated in a manner known per se by means of a bilinear transformation.

In this context, it is also regarded as advantageous if, in the case of the digital filter, the coefficients of the

6 temporally discrete transfer function can be altered. In

this case, the transfer function of the correction element

8 can be matched in a particularly simple manner to transfer

9 functions of the measuring circuit brought about by

10 different voltage sensors.

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One further advantageous development of the method according to the invention also provides for a further-processing arrangement to be used which has a DC isolating element in its input region. The further-processing arrangement and the correction element can thus be DC-isolated from the high-voltage side without any problems.

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In terms of the apparatus, the object on which the invention 19 is based is achieved by a measuring apparatus for measuring 20 the voltage at a point in a power distribution network by 21 means of a measuring circuit, which has a voltage sensor, 22 which is coupled to a current-carrying conductor of the 23 network, and a further-processing arrangement, which is 24 connected to the voltage sensor, and outputs a measured 25 voltage value as the output signal at its output, a 26 correction element being connected to the measuring circuit 27 on the output side in accordance with the invention so as to 28 achieve a correct measured value from the output signal from 29 the measuring circuit, said correction element having a 30 transfer function which is inverse to the transfer function 31 32 of the measuring circuit. Owing to the use of a correction 33 element having a transfer function which is inverse to the 34 transfer function of the measuring circuit, it is possible to achieve accurate measured voltage values with such a 35 measuring apparatus using any desired measuring sensors. 36

- For reasons of cost, provision can advantageously be made for the voltage sensor to be a capacitor device. In accordance with one preferred embodiment, such a capacitor device may also be a coupling capacitor formed from the
- 5 current-carrying conductor of the network and an electrode
- 6 which is DC-isolated from said current-carrying conductor.
- 7 An electrode having this design may preferably be a
- 8 so-called ring electrode.

- 10 As an alternative, however, provision may also be made for
- 11 the voltage sensor to be an inductive voltage transformer,
- 12 which is connected on the primary side to the
- 13 current-carrying conductor.

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- 15 Since such an inductive voltage transformer often already
- 16 produces measured voltage values of a very high quality, in
- 17 this context provision may also be made for it to be
- 18 possible for the correction element to be optionally
- 19 bypassed via a switch.

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- 21 However, even in the case of an inductive voltage
- 22 transformer, the quality of the measured voltage values can
- often be increased further still by the use, according to
- 24 the invention, of a correction element having an inverse
- 25 transfer function, with the result that it is also
- 26 worthwhile in this case to use the correction element, which
- 27 in this case is therefore not bypassed.

- 29 In other words, a measuring apparatus according to the
- 30 invention has, for example, an input terminal for the
- 31 optional connection to any desired voltage sensors, for
- 32 example to the electrode of the coupling capacitor or to the
- 33 secondary winding of an inductive voltage transformer, which
- 34 is connected on the primary side to the current-carrying
- 35 conductor. As a result, it is in this case possible to
- 36 connect the measuring apparatus to the corresponding voltage
- 37 sensor irrespective of whether a coupling capacitor or an
- 38 inductive voltage transformer has already been installed at

- the measurement point in the network. The measuring 1
- apparatus is then provided with a switch for optionally 2
- switching the correction element which simulates the inverse 3
- transfer function on or off in order to switch the 4
- correction element on in the event of a connection to the 5
- coupling capacitor and to switch the correction element off, 6
- if required, in the event of a connection to the voltage 7
- transformer. Even in the case of the inductive voltage 8
- transformer, in this case the correction element could 9
- remain switched on, in which case the inverse transfer 10
- function of said correction element would have to be 11
- correspondingly altered. It would be possible for this to be 12
- carried out in a simple manner, in particular in the case of 13
- a digital filter having a temporally discrete transfer 14
- function as the correction element, by adjusting the 15
- coefficients. 16

17 Depending on whether the output signal from the measuring

- circuit is an analog or a digital output signal, an analog 19
- filter having a PID characteristic or a digital filter can 20
- correspondingly be used. 21

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- One advantageous development of the measuring apparatus 23
- according to the invention provides for the 24
- further-processing arrangement to have a DC isolating 25
- element in its input region. It is thus possible to 26
- DC-isolate the high-voltage part of the measuring apparatus 27
- from the low-voltage part in a simple manner. The DC 28
- isolating element can preferably be an inductive current 29
- transformer. 30

- 32 In accordance with one further advantageous development of
- 33 the measuring apparatus according to the invention, the
- 34 voltage sensor is connected on the output side to a series
- circuit comprising a resistor having a high resistance value 35
- and the primary winding of the inductive current 36
- transformer. The input voltage of the further-processing 37
- arrangement is converted to a comparatively low current via 38

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the resistor having a high resistance value such that the 1 2 inductive current transformer can be designed to be comparatively small and thus inexpensive. 3 4 One further advantageous development of the measuring 5 apparatus according to the invention also provides for the 6 secondary winding of the current transformer to be loaded by 7 a negative feedback operational amplifier with an internal 8 resistance of 0 ohm. In turn, a current/voltage conversion 9 takes place using the operational amplifier, in which case 10 the range of the level of the resulting voltage can be 11 adjusted by the negative feedback of the operational 12 amplifier, for example via a resistor arranged in the 13 negative feedback path. 14 15 In addition, one advantageous embodiment of the measuring 16 apparatus according to the invention is regarded as the fact 17 that the measuring circuit has an analog-to-digital 18 converter on the output side in order to generate digital 19 output signals from the measurement arrangement. 20 21 The invention will be explained in more detail below with 22 reference to an exemplary embodiment illustrated in the 23 figure. The figure shows the circuit diagram of a measuring 24 apparatus MV for voltage measurement using a digital filter 25 as the correction element KG in order to correct the 26 measured voltage values. 27 28 A current conductor 1 of a power distribution network forms 29 an electrode of a capacitive voltage transformer as the 30 voltage sensor SG in the form of a high-voltage coupling 31 32 capacitor 2. The other electrode of the coupling capacitor 33 2, which is preferably passed around the current conductor 1 34 in annular fashion such that it is DC-isolated from said current conductor 1, is connected to an input terminal 3 of 35

a further-processing arrangement WA of the measuring

apparatus MV. In a similar manner, other forms of capacitive

voltage transformer are also possible as the voltage sensor

- 1 SG, however. As illustrated in the figure, the capacitive
- 2 voltage transformer may optionally be a capacitive divider,
- 3 whose low-voltage capacitor is represented by dashed lines
- 4 in the figure. An embodiment in the form of a capacitive
- 5 divider is not absolutely necessary, however. Instead, as is
- 6 indicated by the further dashed line, the secondary winding
- of an inductive voltage transformer 4, which is connected on
- 8 the primary side to the current conductor 1, can also be
- 9 connected to the input terminal 3 of the further-processing
- 10 arrangement WA. As is indicated in the figure by the curved
- 11 bracket, the voltage sensor SG and the further-processing
- 12 arrangement WA together form a so-called measuring circuit
- 13 MS.

- 15 The text which follows will consider the case in which the
- 16 coupling capacitor 2 as the voltage sensor SG is connected
- 17 to the input terminal 3 of the further-processing
- arrangement WA. A series resistor 5 (Rv), which generally
- 19 has a high resistance value and is arranged downstream of
- 20 the input terminal 3, carries out a voltage/current
- 21 conversion of the voltage, which has been tapped off
- 22 capacitively at the electrode, which is DC-isolated from the
- 23 current conductor 1, of the coupling capacitor 2, to a
- 24 displacement current. In addition, the series resistor 5
- 25 forms, with the capacitance of the coupling capacitor 2, a
- 26 high-pass filter and therefore improves the input-side EMC
- 27 (electromagnetic compatibility) performance of the measuring
- 28 apparatus MV.

- 30 A DC isolating element, which is connected on the primary
- 31 side in series with the series resistor 5 and is in the form
- 32 of an inductive current transformer 6, on the one hand
- 33 serves the purpose of potential isolation and, on the other
- 34 hand, serves the purpose of reducing the coupling
- 35 capacitance with respect to the high-voltage conductor and
- 36 thus brings about further EMC shielding. Owing to the
- 37 displacement current which is low as a result of the

dimensions of the series resistor 5, the inductive current 2 transformer 6 can be designed to be relatively small. 3 An operational amplifier 7 having a feedback resistor 8 (Rm) 4 is connected to the secondary side of the inductive current 5 transformer 6. The operational amplifier 7 acts as an active 6 load for the inductive current transformer 6 with an 7 internal resistance of 0 ohm. At the same time, the 8 operational amplifier 7 takes on the function of 9 current/voltage conversion and converts the current produced 10 by the inductive current transformer 6 to a voltage. The 11 ratio between the output voltage and the input current of 12 the operational amplifier 7 is determined by the value Rm 13 for the feedback resistor 8. This value can be switched over 14 by means of a link or an analog switch, as indicated in the 15 figure, in order to be able to match the driving of the 16 current transformer 6, which driving is dependent on the 17 coupling capacitor 2 or the voltage transformer 3, to the 18 measurement range of an analog-to-digital converter 9 19 downstream of the operational amplifier 7. 20 21 Said analog-to-digital converter 9 converts its input 22 voltage to a digital sample sequence. 23 24 If the input terminal 3 of the further-processing 25 arrangement WA is connected to the inductive voltage 26 transformer 4, the transfer performance of the measuring 27 circuit MS formed from the voltage sensor SG (i.e. in this 28 case the inductive voltage transformer 4) and the 29 further-processing arrangement WA is independent of the 30 frequency in the relevant frequency range (50 or 60 Hz). 31 32 33 In contrast, in the event of a connection to the coupling 34 capacitor 2, the following transfer function for the

measuring circuit MS to the analog-to-digital converter 9

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results:

$$1 \qquad \frac{U_A}{U_{\text{Prim}}} = \frac{j\omega C_D \cdot R_m}{1 + j\omega C_D \cdot R_v}$$

where U_A is the voltage at the output of the operational 3 amplifier 7, U_{Prim} is the voltage of the current conductor 1, 4 and C_{D} is the capacitance of the coupling capacitor 2. If the 5 value for U_A resulting using this transfer function is left 6 7 unchanged, a measured voltage value is obtained which is completely unsuitable for accurate voltage measurement. The 8 9 transfer function of the entire measuring apparatus MV (comprising the voltage sensor SG, the further-processing 10 arrangement WA and the correction element KG) therefore 11 needs to be corrected by a downstream correction element KG 12 by means of a transfer function which is inverse to the 13 transfer function of the measuring circuit MS. This 14 correcting inverse transfer function of the correction 15 element KG should be formed in accordance with the following 16 17 equation:

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$$G_{corr} = \frac{1 + j\omega C_D \cdot R_v}{1 + j\omega T_v}$$

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The resultant transfer function of the entire measuring 21 apparatus MV in turn represents a high-pass filter, but with 22 a new cut-off frequency $1/(2*pi*T_K)$. The time constant T_K can 23 in this case be selected such that the cut-off frequency is 24 below the frequency range to be detected for the measured 25 voltage value, with the result that the transfer function of 26 the entire measuring apparatus MV is linear in this 27 frequency range. It is particularly advantageous if T_K is 28 equal to the time constant of the current transformer used 29 for detecting the current signals, which are likewise 30 31 measured at the same time as the voltage signal. 32

33 If, as shown in the figure, a digital filter 10 is used to correct the transfer function of the measuring circuit MS, 34 the correcting transfer function G_{corr} can previously be 35 transformed into a temporally discrete transfer function G(z 36

1 1). This takes place with the aid of the bilinear

2 transformation

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$$4 \qquad e^{-j\omega T_A} = \frac{2}{T_A} \cdot \frac{z+1}{z-1} \ .$$

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6 The right-hand side of this equation is the series

7 expansion, terminated after the first element, of the

8 function $e^{-j\omega \cdot T}$. This gives:

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$$G(z^{-1}) = \frac{a_1 z^{-1} + a_0}{1 + b_1 z^{-1}}$$
,

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where z^{-1} is the delay of a sampled value by a sampling

interval; a_0 , a_1 and b_1 are coefficients of the temporally

14 discrete transfer function. This temporally discrete

transfer function $G(z^{-1})$ is implemented by the digital filter

16 10 illustrated in the figure. This in turn has a final

amplification at the frequency 0, with the result that the

numerical stability of the apparatus is ensured even in the

19 case of an offset of the analog-to-digital converter 9.

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21 A switch 11 is used to connect the output of the

22 analog-to-digital converter 9 to the measured value output

23 12 of the measuring apparatus MV either directly or via the

24 digital filter 10. The direct connection can be selected if

25 the inductive voltage transformer 4 as the voltage sensor SG

26 is connected to the input terminal 3 of the

27 further-processing arrangement WA, and the connection via

28 the digital filter 10 is selected if the coupling capacitor

29 2 as the voltage sensor SG is connected to the input

30 terminal 3. The switch 11 could, however, also be dispensed

31 with, with the result that, in both cases, the digital

32 filter 10 is included since an improvement in the quality of

33 the measured voltage values can be achieved owing to the

34 shift in the cut-off frequency of the transfer function of

35 the entire measuring apparatus MV even in the case in which

36 the inductive voltage transformer 4 is used. However, the

coefficients of the digital filter 10 can in each case be adjusted differently for the connection to the inductive 2 voltage transformer 4, on the one hand, and to the coupling 3 capacitor 2, on the other hand. 4 5 Correspondingly, a measuring apparatus can also be 6 implemented using analog voltage signals, in which case an 7 analog filter would be used in place of the digital filter, 8 and the analog-to-digital converter would be dispensed with. 9